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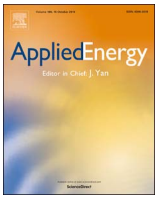

Systematic investigation on combustion characteristics and emission-reduction mechanism of potentially toxic elements in biomass- and biochar-coal co-combustion systems

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HIGHLIGHTS

- The study investigates thermal-characteristics and migration of PTEs during biochar-coal combustion.
- Biochar-coal blends improved thermal behavior compare to coal/biomass-coal fuels.
- Soot yield and un-burned C in fly ash reduced significantly in biochar blended fuels.
- Volatilization of PTEs during co-firing of biochar-coal blends reduced considerably.
- Biochar-coal blend can be used in power plants for emission-reduction of PTEs.

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ABSTRACT

Thermochemically converted biochar is considered as one of the promising alternative solid-fuel due to its high carbon contents of up to 80%, and has great potential to produce environmentally-friendly green-energy by improved fuel properties and emission-reduction of potentially toxic elements (PTEs). In this study, the biochar fuels, produced from peanut shell (PS) and wheat straw (WS) at 300, 500 and 700 °C, alone and blended with coal at mass ratio of 20% and 50% were systematically investigated for combustion characteristics and their potential to reduce the emission of PTEs including As, B, Ba, Be, Bi, Cd, Co, Cr, Cu, Ga, Ni, Pb, Sb, Sn, V and Zn in relation to partitioning, retention and volatilization in the co-combustion systems, using a variety of experimental techniques. Results indicated that the biochar-coal blended fuels in equal proportion showed steady state combustion over broad temperature range resulting increased the combustion efficiency and improved the thermal characteristics in comparison to coal and/or biomass-coal fuels. In addition, soot yield, CO emission and un-burned carbon in fly ash reduced significantly in biochar-blended fuels. However, CO_2 emission from biochar-coal co-combustion was comparable to coal and/or biomass-coal fuels. Moreover, the present study illustrated that the volatilization potential of PTEs during combustion of biochar and their blends with coal decreased considerably up to 21% compared to that of coal, and enrichment of these contaminants occurred in the bottom and fly ashes ranged from 15.38–65% and 24.54–74.29%, respectively. Slagging and fouling problems were still found with biochar-coal co-combustion due to the higher inorganic fraction of biochar, which were overcome with the hydrothermal washing of fuels. Thus, it can be concluded that biochar-coal co-combustion is a suitable option for its use in existing coal-fired energy generation system to achieve the sustainable clean-green energy and reduction of gaseous PTEs emission.

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1. Introduction

The use of renewable energy resources as an alternative to conventional non-renewable fossil fuel resources has currently received attention worldwide [1]. This transition is primarily due to depletion of fossil fuels and environmental concerns such as greenhouse gases (GHGs) emission and release of potentially toxic elements through flue gas during coal combustion. The potentially toxic elements are any metallic elements (As, Ba, Bi, Cd, Cr, Cu, Ga, Ni, Pb, Sb, Sn, Zn, etc.) having the potential to cause severe health hazards if present in excessive concentration. Moreover, their emission in the environment is an issue of key concern nowadays due to their persistence in nature and chemical stability in both aquatic and terrestrial ecosystems [2]. Furthermore, chronic exposure of these PTEs to living organisms, present in the environment, has accumulation potential in various body parts and can cause different abnormalities in humans [3–4].

Currently, renewable energy meets ~16% primary energy demands on a global scale [5]. Renewable resources, particularly biomass materials, are the fastest growing energy source on earth system according to current International Energy Outlook report [6]. For example, the generation of renewable electricity in the USA from biomass is projected to be triple by 2040. As plant materials have fixed carbon in lignocellulose form during their growth by photosynthesis process and thus these are carbon negative due to no net contribution in greenhouse effect with combustion. Thus, in comparison to stand-alone biomass combustion, biomass-coal blends co-utilization in existing coal-fired power plants is appealing these days because no additional cost or substantial investment is required [7]. Biomass-coal combustion also causes NO_x and SO_2 gaseous pollutants emission reduction due to low sulfur (S) and higher volatile contents of biomass [8]. Additionally, co-combustion is an effective approach to disposing of the crop residuse, otherwise, on farm burning generates particulate matter (5–12%) that deteriorate air quality and caused severe issues recently [9]. Extensive research on co-firing of different lingo-cellulose biomass materials such as brewer's spent grains, wheat straw, rice husk and pine sawdust, with coal has been carried out recently [10–13].

However, there are several technical challenges associated with biomass intrinsic properties that limit its application in existing co-fired energy production system. These issues are higher contents of alkali-alkaline earth metals and halogens in biomass materials that cause fouling, slagging or corrosion problems in boiler during operation [14–15]. Other drawbacks are higher oxygen contents resulting low energy density caused flame instability during co-combustion, poor grindability due to fibrous structure thus more energy is required for grinding process as well as higher moisture and volatile matter contents of feedstock biomass [16]. All these concerns vary with biomass type and their physico-chemical properties; limit the potential economic utility of biomass materials for energy generation due to poor thermal efficacy and more air pollutants emission [17–18]. Moreover, the co-utilization of biomass with coal can redistribute PTEs in different phases such as in bottom ash, fly ash and flue gas. The processes involved in PTEs speciation are crucial as these influence the emission characteristics of PTEs. The partitioning and migration behavior of PTEs in different combustion products vary with vaporization/condensation potential of particular element volatile species, initial content, occurrence modes such as physisorption or chemisorption, fuel type, and air pollution emission control devices, as well as design and operational conditions of combustion system [2]. Emission behavior of PTEs during coal/biomass and their blends combustion have been focused recent years [19–21]. Thus, to overcome all these downsides and meet the challenges of existing coal fired power generation system it is necessary to upgrade the fuel properties of biomass prior to use in the co-utilization system.

In this regard, pyrolysis is an attractive thermochemical conversion technology to improve the biomass fuel properties and restricts the release of PTEs by stabilizing these in biochar. Pyrolytic yields, i.e., bio-oil solid fuel (biochar), syngas and variety of other valuable chemicals depending upon process operating conditions such as highest heating temperature (HHT), retention time, heating and sweep gas flow rates, and pyrolysis environment [14,22–24]. In a comparison of raw biomass feedstock, the pyrolytic product biochar has improved fuel properties such as higher energy density, higher calorific value, high carbon and low oxygen content, and less emission of GHGs [8,25–26]. Moreover, pyrolysis also immobilized the PTEs in biochar due to higher fixed carbon and alkaline nature, which may reduce the PTEs emission during combustion process [27–28]. Thus, co-combustion of biochar with coal in existing power plants likely results multiple, technological, economic and environmental benefits.

Knowledge about the combustion and kinetic characteristics of individual or blended fuels are crucial for the designing of co-fired energy generation system [10]. Thermo-gravimetric analysis (TGA) is an important and most commonly employed technique to investigate the thermal behavior and kinetics of solid fuels such as biomass, coal and their blends in different proportion [9]. It enables to measure the rate of change of sample mass with time as the function of temperature. Thermal decomposition and combustion stages temperatures can also be determined using TGA. Furthermore, kinetic parameters such as activation energy of fuels individual combustion stages could be calculated [10,29].

The availability of low-cost, good quality biomass material is a prerequisite for commercial-scale production and use of biochar in the co-firing system [23]. Peanut shell (PS) and Wheat straw (WS) biomass materials are abundantly available agricultural crop residues used in this study. Efforts to investigate the combustion characteristics and thermal behaviors of various biomasses under co-combustion system have focused extensively in previous studies. However, limited studies address biochar importance as a solid fuel to improve both thermal behaviors and emission-reduction of PTEs during co-combustion system. The overall objectives of this study were (1) to assess the influence of pyrolysis temperature on fuel properties of the peanut shell and wheat straw derived biochars. (2) to investigate the thermal behavior and reaction kinetics of raw biomass, biochars, coal and their blends during combustion by using the thermogravimetric analyzer. (3) The effect of pyrolysis on the partitioning behavior of PTEs in different phases and their emission characteristics (volatilization potential) during coal/pyrolytic products co-utilization in an energy generation system.

2. Material and methods

2.1. Collection and preparation of materials

The Bituminous coal (C) having low ash content (~13%), selected for use in this study, obtained from Huainan Coalfield (Anhui, China) that mostly utilized for the generation of electricity in coal-fired Pingwei power station. Abundantly available agricultural waste biomass materials, peanut shells (PS) and wheat straws (WS) were chosen, obtained from the Anhui province of China for this study. The coal and biomass raw material samples were air dried, milled with a laboratory scale grinder (Model 4 Wiley® Thomas Scientific, USA) and sieved to attain a homogenized particle size fraction in the range of 50–100 mesh.

2.2. Biomass pyrolysis and experimental process

The schematic diagram of the fixed bed split furnace system (model BTF-1200C, Anhui BEQ equipment, technology Co., Ltd, China) used in this study is illustrated in Fig. 1. Slow-pyrolysis was conducted at 300, 500 and 700 °C by taking approximately 30 g of air-dried and ground biomass material in ultra-high purity quartz boat and placed inside the center of the reactor tube. The residual air was purged by using a constant supply of argon from one side of the tube with 50 ml min^{-1}